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The Thermal Expansion and Thermophysical Properties of an Aluminum and Al/B_4C composite

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Abstract. The paper presents results of experimental studies of the thermal expansion and thermophysical properties of an Al/B_4C composite with a boron carbide content of 20 wt% and technically pure aluminum in the temperature range from 100 to 600°C to evaluate the possible use of this composite as a neutron-protective material in the nuclear industry.

INTRODUCTION

At present, aluminum-matrix composites containing dispersed particles of silicon and boron carbides (Al/SiC and Al/B_4C) find a wide application in aircraft industry, automotive industry, electrical engineering and nuclear power industry as structural, wear-resistant, ballistic and functional materials [1, 2] A layered Al/B_4C composite with cladding layers of aluminum alloys, supplied by foreign manufacturers under the BORAL trade mark, are widely used in the nuclear industry for the manufacture of structural components for spent nuclear fuel shipping containers. The most important functional property of these materials is the ability of the Al/B_4-composite layer to absorb slow thermal neutrons, which is most effectively manifested when the content of boron carbide exceeds 20 wt%. The mechanical and neutron-protective properties of the Al/B_4 composite essentially depend on the shape of the dispersoids of boron carbide (fiber, particle), its content in the range of 20 to 40 wt%, as well as on the method of composite production (powder metallurgy, extrusion in the liquid phase, hot rolling, spark plasma sintering, etc.) [3–6]. Alongside the necessary mechanical and functional properties, Al/B_4C composites used in shipping packaging sets must have a thermal expansion coefficient close to aluminum and its alloys, as well as the necessary thermophysical properties (heat capacity, thermal conductivity and thermal diffusivity) to ensure passive removal of the heat generated by the spent nuclear fuel assembly, provided that the outside surface temperature of the product does not exceed 85 °C [4]. Therefore, the thermophysical properties of the Al/B_4C composite are an important attestation characteristic of the material for compliance with nuclear safety standards in the transportation of radioactive materials. The thermophysical properties of nuclear power materials can vary widely, depending on the temperature, the effects of gamma and neutron radiation, pressure and the production method [7]. The purpose of this work is a comparative study of the temperature dependences of the characteristics of thermal expansion and the thermophysical properties of commercially pure aluminum and a monolithic Al/B_4C composite, and a comparison of the experimental data with reference data for sintered commercially pure aluminum and boron carbide.

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SAMPLES AND RESEARCH METHODS

The thermophysical properties were studied on samples of commercially pure aluminum and Al/B_4C composites (20 wt% B_4C) obtained by powder metallurgy, by hot rolling of powders. To produce a sintered sample of commercially pure aluminum, PA-4 aluminum granular powder with granules sized 50 to 200 μm was used. To create the composite matrix, PA-4 aluminum powder was used, along with 20% boron carbide powder of the fraction ≤ 25 μm as the filler (Fig. 1). Rolling of aluminum powder and its mixture with boron carbide was carried out in the region of aluminum melting temperatures in the Plastometriya collective use center of the Institute of Engineering Science, RAS (Ural Branch), using a Duo rolling mill, at a speed of 0.01 to 0.08 m/s. The Al/B_4C composite production technology was described in detail in [8, 9]. In order to study the phase composition and microstructural transformations of Al/B_4C composites, X-ray diffraction analysis was performed. The studies were carried out on a Shimadzu XRD-7000 diffractometer in K-radiation.

Dilatometric studies were carried out on a Linseis L75VS5LT high-temperature vertical dilatometer at temperature ranging from 20 to 600 °C. The mean values of the thermal expansion coefficient were calculated from the experimental data by the formula

$$\alpha = \frac{1}{ln} \times \frac{lt - ln}{t - tn}, \tag{1}$$

where α is the mean thermal expansion coefficient; lt and ln are the linear sample dimensions the current temperature t and 20 °C.

The thermophysical properties were measured at temperatures ranging from 100 to 600 °C by a Netzch LFA 457 laser flash devices and a Netzch STA 449C synchronous thermal analysis device in the Unikum collective use center at the Ural Federal University named after the first President of Russia B. N. Yeltsin.

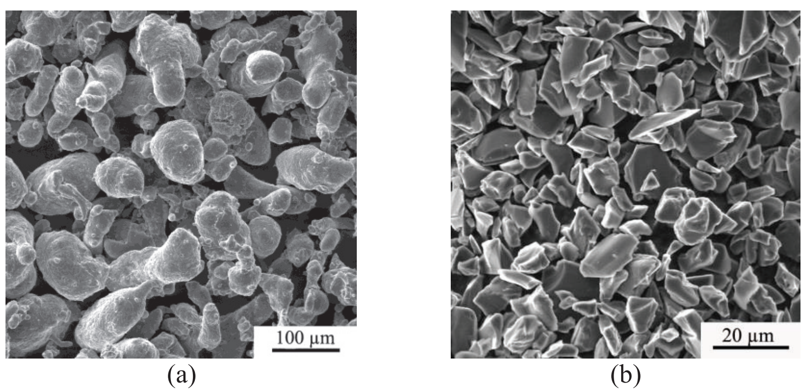


FIGURE 1. An SEM image of powder morphologies: Al (a) and B_4C (b)

RESULTS AND DISCUSSION

The X-ray phase analysis has detected the presence of two phases of the Al solid solution and boron carbide B_4C in the Al/B_4C composite (Fig. 2).

The results of studying thermal expansion and determining the thermal expansion coefficient of commercially pure aluminum and Al/B_4C composites in the temperature range from 20 to 600 °C are shown in Fig. 3. The dilatometric curves for commercially pure aluminum and the Al/B_4C composites have a linear growth pattern with increasing test temperature. In this case, the thermal expansion and thermal expansion coefficient of aluminum are higher than those of the Al/B_4C composite. In accordance with the requirements of nuclear safety, the thermal expansion coefficient of nuclear power materials must be minimal in order to avoid the harmful effects of thermal stresses arising in the construction of spent nuclear fuel shipping containers when the temperature drops. The average values of the thermal expansion coefficient obtained from the calculations of the experimental data are $\alpha = 18.4\times10^{-6}\,K^{-1}$ for aluminum and $\alpha=15\times10^{-6}\,K^{-1}$ for the Al/B_4C composite. From the reference data [10, 11], the mean thermal expansion coefficient for boron carbide in the range from 40 to 600 °C is $4.2\text{-}4.6\times10^{-6}\,K^{-1}$. Thus, an increase in the proportion of boron carbide in the composite can significantly reduce the values of the thermal expansion coefficient of the matrix composite.

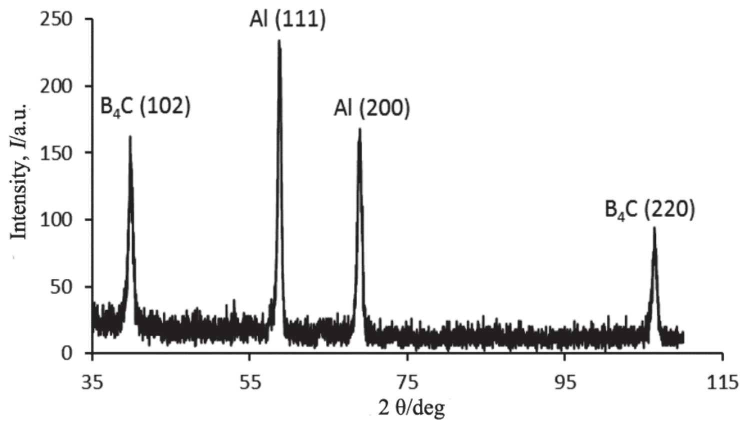


FIGURE 2. XRD patterns of the Al/B_4C composite

According to the experimental data, sintered commercially pure aluminum has good thermal conductivity, which reaches about 300 W/(m·K) at a temperature of 100 °C, but drops sharply to 230 W/(m·K) with increasing test temperature. Probably, this is due to the active oxidation of free intergranular surfaces in the powders and the growth of oxide films (Fig. 4 a).

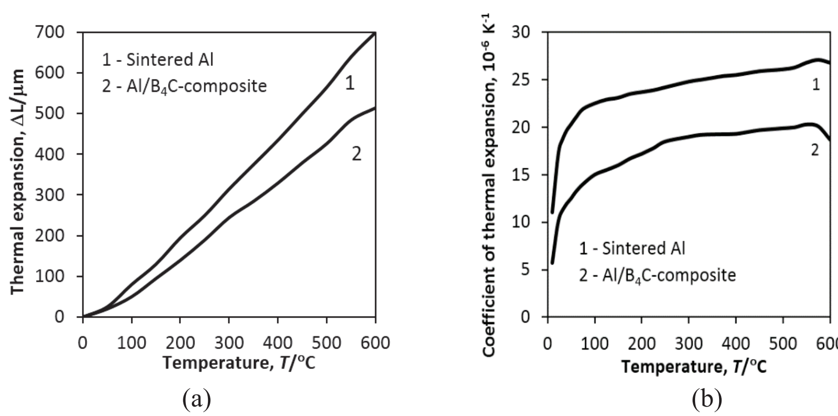
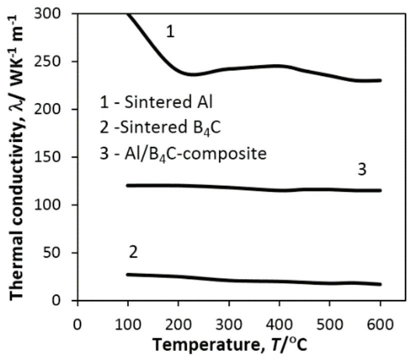


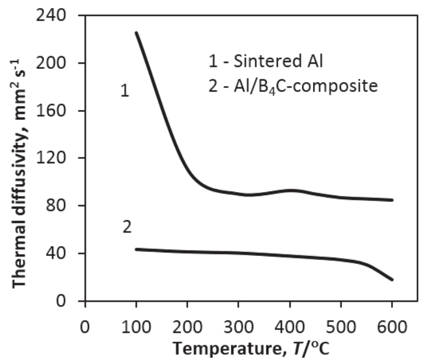
FIGURE 3. Thermal expansion (a) and coefficient of thermal expansion (b) of sintered aluminum and the Al/B_4C composite

The experimental values of the thermal conductivity of sintered aluminum do not coincide with the reference data for pure aluminum obtained by casting, which is characterized by a gradual increase in the thermal conductivity from 213 to 282 W/(m·K) at temperatures ranging between 100 and 600 °C [12]. The low values of the thermal conductivity of sintered aluminum are due to the presence of multiple intergranular boundaries in the powders, the presence of defects in the form of pores and the presence of a thin oxide film on the surface of the granules. All of these factors act as a barrier to heat transfer from one granule to another and lead to a decrease in thermal conductivity [13]. It is known from the reference data [14] that the thermal conductivity of powdered high-density boron carbide decreases from 28 to 17 W/(m·K) in the range of the investigated temperatures.

The coefficient of thermal conductivity of boron carbide is much lower than that of aluminum; therefore, an increase in the proportion of boron carbide in the Al/B_4C composite leads to a decrease in the thermal conductivity of the material. This explains the fact that the thermal conductivity curve for the Al/B_4C composite occupies an intermediate position between the aluminum and boron carbide curves in the graph of the temperature dependence of thermal conductivity. The thermal conductivity curve for the Al/B_4C composite has a smooth decreasing slope with increasing temperature throughout the measurement interval. The thermal conductivity of the Al/B_4C composite varies from 120 to 115 W/(m·K). A similar trend of decreasing thermal conductivity at the elevated temperatures can be explained by the oxidation of the samples and the growth of oxide films in the free volumes of the compacted powder samples. The data obtained is consistent with the results of the study of the thermal conductivity of the Al/B_4C composites produced by extrusion and plasma spraying [3, 4].



(a)



(b)

FIGURE 4. Thermal conductivity (a) and thermal diffusivity (b) of the Al/B_4C composite, sintered aluminum and boron carbide [14]

Based on the analysis of the analytical model of an emergency for spent nuclear fuel shipping containers (TUK-84) according to OST B95.2605-90 [4], we have established that, with the thermal conductivity of the material of the spent nuclear fuel shipping containers of 1.2 W/(m·K), natural cooling of the fuel assemblies is provided, this value being much lower than the thermal conductivity values of the Al/B_4C composite studied.

With increasing temperature, the thermal diffusivity of the investigated materials also decreases (Fig. 4 b). Aluminum is characterized by a sharp decrease in thermal diffusivity in the range from 100 to 200 °C, which is caused by active oxidation of free intergranular surfaces in the powders and the growth of oxide films. At 600 °C the thermal conductivity of the Al/B_4C composite falls significantly and amounts to 40% of the thermal diffusivity at room temperature.

The graphs of the change in the heat capacity of the Al/B_4C composite and its initial constituents with increasing temperature are shown in Fig. 5. As can be seen, the heat capacity of aluminum naturally increases from 0.5 to 1 J/(g·K) in the range from 100 to 600 °C. It was shown in [15] that the heat capacity curve of boron carbide also goes up smoothly in the same temperature range, but slightly higher, from 1 to 2 J/(g·K). Therefore, it is fully understandable that, for the Al/B_4C composite, the heat capacity curve occupies an intermediate position between the curves of its original constituents. At temperatures above 550 °C, when the aluminum matrix is in a state close to the molten one, a sharp jump in specific heat is characteristic of the composite. However, it should be noted that these sharp jumps are not typical for the heat capacity curve of aluminum when temperatures close to melting are reached.

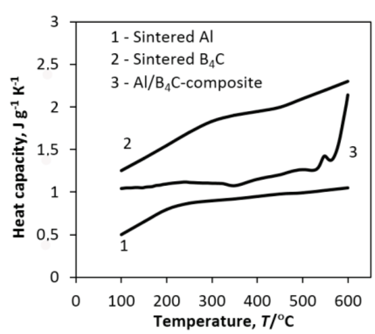


FIGURE 5. Heat capacity of the Al/B_4C composite, sintered aluminum and boron carbide [15]

CONCLUSION

On the basis of the conducted research, it has been established that the thermal expansion of sintered commercially pure aluminum and that of a monolithic Al/B_4C composite increase qualitatively in the same way. The difference between these characteristics increases as the temperature rises from 20 to 600 °C, but it does not exceed 30%. Based on the analysis of the thermophysical properties of the Al/B_4C composite and its initial constituents, it has been established that the Al/B_4C composite is somewhat inferior to pure aluminum in terms of the thermophysical properties studied, with the exception of the heat capacity parameter, due to a 20% boron carbide content. However, the investigated Al/B_4C composite satisfies the requirements of the nuclear industry for neutron-protective materials, and it can be used as a material for spent nuclear fuel shipping containers.

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REFERENCES

1. N. Chawla and K. N. Chawla, *Metal Matrix Composites*, 2nd edition (Springer Science + Business Media, New York, 2013), 370 p.
2. N. B. Pugacheva, N. S. Michurov and T. M. Bykova, FMM **117**, 654 (2013).
3. V. N. Gulbin, Nuclear Physics and Engineering **2** (3), 272 (2011).
4. V. G. Ivanov, V. I. Gorynin and I. A. Schastlivaya, Problems of Materials Science **4** (60), 20 (2009).
5. R. M. Mohanty, K. Balasubramanian, S. K. Seshadri, Materials Science and Engineering A **498** (1), 42 (2008).
6. P. Zhang, Y. Li, W. Wang, Z. Gao, B. Wang, Journal of Nuclear Materials **437**, 350 (2013).
7. V. S. Chirkin. *Thermophysical Properties of Nuclear Materials* (Atomizdat, Moscow, 1968), 485 p.
8. S. V. Gladkovsky, T. A. Trunina, E. A. Kokovikhin and S. V. Smirnova, RF Patent No. 2465094 (2012).
9. S. V. Gladkovsky, T. A. Trunina, E. A. Kokovikhin, S. V. Kuteneva and I. S. Kamantsev, RU Patent No. 2528926 (2014).
10. V. S. Chirkin, *Thermophysical Properties of Materials* (Fizmatgiz, Moscow, 1959), p. 356.
11. F. Thévenot, Journal of the European Ceramic Society **6** (4), 205 (1990).
12. P. L. Kirillov, P. G. Bogoslovsky, *Heat and Mass Transfer in Nuclear Power Plants* (Energoatomizdat, Moscow, 2000), 456 p.
13. N. Burger, A. Laachachi, M. Ferriol, M. Lutz, V. Toniazzo and D. Ruch, Progress in Polymer Science **61**, 1 (2016).
14. T. Maruyama and S. Onose, Journal of Nuclear Science and Technology **36** (4), 380 (1999).
15. B. A. Kushunin, Report of GP MZP Normative Base of Rosatom (1999).